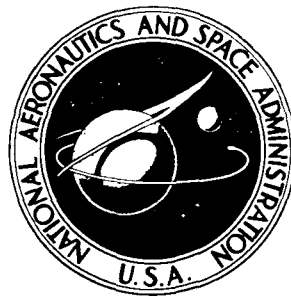


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**PERFORMANCE OF HIGH-AREA-RATIO
ANNULAR DUMP DIFFUSER USING
SUCTION-STABILIZED-VORTEX FLOW CONTROL**

Albert J. Jubasz and John M. Smith

Lewis Research Center

Cleveland, Ohio 44135

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16. Abstract A short annular dump diffuser having a geometry conducive to formation of suction stabilized toroidal vortices in the region of abrupt area change was tested. The overall diffuser area ratio was 4.0 and the length-to-inlet height ratio was 2.0. Performance data were obtained at near ambient temperature and pressure for inlet Mach numbers of 0.18 and 0.30 with suction rates ranging from 0 to 18 percent of total inlet mass flowrate. Results show that the exit velocity profile could be readily biased toward either wall by adjustment of inner and outer wall suction rates. Symmetric exit velocity profiles were inherently unstable with a tendency to revert to a hub or tip bias. Diffuser effectiveness was increased from about 38 percent without suction to over 85 percent at a total suction rate of 10 to 12 percent. At the same time diffuser total pressure loss was reduced from 3.1 percent to 1.1 percent at an inlet Mach number of 0.3.					
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PERFORMANCE OF HIGH-AREA-RATIO ANNULAR DUMP DIFFUSER

USING SUCTION-STABILIZED-VORTEX FLOW CONTROL

by Albert J. Juhasz and John M. Smith

Lewis Research Center

SUMMARY

A short annular dump diffuser designed for improved flow expansion by means of a suction-stabilized toroidal vortex, established on both walls in the region of abrupt area change, was tested at near ambient inlet pressure and temperature. The test program consisted of a vortex-chamber-geometry screening phase followed by a detailed performance test phase of the best geometry. Velocity profile and diffuser pressure recovery performance data were obtained for nominal inlet Mach numbers of 0.18 and 0.30 with suction rates ranging from 0 to 18 percent of total inlet mass flowrate. The included divergence angle of the diffuser approach section was 7° over an approach length of 1.25 inlet heights, resulting in an approach or prediffuser area ratio of 1.15. The overall diffuser exit-to-inlet area ratio was 4.0 and the length-to-inlet height ratio, as determined by the location of a variable position vortex ring or fence, varied from approximately 1.35 to 1.85. Exit velocity profile and pressure measurements were taken downstream of the vortex fence at distances equal to 2, 4, and 6 times diffuser inlet height.

The best chamber geometry resulting from the screening program was found to be one having inner and outerwall suction slots with radial gaps of 0.15 times inlet height and axial gaps of 0.45 times inlet height. Results also show that the diffuser exit velocity profiles, which were typical of annular jets without suction, could be readily flattened and biased toward hub (inner wall), or tip (outer wall) by adjusting the inner and outer wall suction rates. It was not possible to obtain symmetric exit velocity profiles over the entire annular circumference. Such profiles could only be achieved over narrow sectors of the exit annular passage, and even there they were inherently unstable with a tendency to slowly oscillate from a hub-skewed to a tip-skewed profile. Diffuser effectiveness, that is diffuser static pressure recovery, was increased from about 38 percent without suction to over 85 percent at a total suction rate of 10 to 12 percent, depending on the height and position of the vortex fence. This improved diffuser performance was also reflected in a reduction in total pressure loss from 3.1 to 1.1 percent at an inlet Mach number of 0.3.

INTRODUCTION

An investigation was conducted to determine the performance of a short annular dump diffuser designed for improved flow expansion by means of suction-stabilized toroidal vortices. Such a diffuser, having a toroidal vortex maintained on each wall by suction, operates on the principle of a two-dimensional diffuser with rotating cylindrical walls; the rotation of the solid boundary in the direction of flow reduces the adverse wall pressure gradients, thus permitting flow expansion to higher area ratios without separation. The toroidal wall vortices, rotating preferentially with the flow, perform similarly to a rotating solid cylindrical wall, with the added advantage that the axis of rotation need no longer be straight but can be forced to become circular. Hence, a toroidal vortex ring is ideally suited for accelerating boundary layer flow in annular diffusers.

The use of standing vortices to control flow expansion was proposed by Ringleb (ref. 1) based on observations of mountain ridge vortex flows which cause snow cornice formation. Hence the Ringleb diffuser was designed with precisely contoured cusps in the diffuser walls for vortex trapping, but no means of replenishing vortex energy dissipated by wall friction was provided. As was pointed out in reference 2, such a diffuser has only limited performance potential due to the difficulty of maintaining stable vortices in the cusps. To demonstrate a solution to this problem, a two-dimensional duct with a variable step area change on its lower wall, followed by a suction slot, was tested in reference 2. Results showed that smooth expansion of the flow downstream of the step area change could be obtained without an aerodynamically designed cusp if sufficient suction per unit wall span was applied. In reference 3 similar conclusions were reached from tests, concerning the effect of suction on flow through a pipe with an abrupt area change. The required suction flow was found to vary with the suction slot design. The best suction slot design determined in reference 3 was incorporated in an annular diffuser with an abrupt area change in reference 4. Although the results clearly illustrated the beneficial effect of suction on diffuser performance, the maximum diffuser effectiveness was limited to 52 percent, indicating that a stable vortex had not been achieved downstream of the step area change. Placing a perforated plate downstream of the diffuser dump plane resulted in improved performance, as indicated in reference 5. This suggested that a stable vortex could be maintained more readily when a solid wall was placed downstream of the vortex. Similar conclusions were reached in reference 6 which reports results obtained with an annular step area change diffuser having flat walls, referred to as "fences," placed downstream of both the hub and tip vortices, which were stabilized by suction. These vortex fences were designed to form a partially enclosed vortex chamber with the upstream walls of the diffuser. In this respect the diffuser design resembled that of references 4 and 5, but for suction slots which are wide enough to permit vortices to be formed inside, rather than downstream, of the suction chamber.

To obtain detailed performance data on a vortex fence diffuser of this type, a modified version of the diffuser used in references 4 and 5 was tested in the present investigation. The downstream wall of that diffuser was detached. Provisions were provided to mount downstream walls (i. e. , fences) of varying heights with lateral adjustment of wall position, thereby varying the width of the suction slot. The diffuser approach section or prediffuser had an included divergence angle of 7° , resulting in an area ratio of 1.15. The overall diffuser area ratio was 4.0 and the nominal diffuser length was 1.5 times diffuser inlet height. The diffuser inlet passage flow area was 304 square centimeters (47.12 in.^2). Radial profiles of velocity, diffuser effectiveness (static pressure recovery) and total pressure loss data were obtained in a large number of circumferential planes for nominal inlet Mach numbers of 0.18 and 0.30 with suction rates varying from zero to 18 percent. All testing was conducted with air at ambient temperature and pressure.

SYMBOLS

A	area
AR	diffuser area ratio
B	bleed-flow fraction of total mass-flow rate
g_c	dimensional constant
H	diffuser inlet passage height
L	distance from vortex fence to exit pitot static rakes
M	average Mach number at an axial station
$\dot{m}$	mass-flow rate
P	average pressure at an axial station
p	local pressure at a radial position
R	gas constant for air
S	suction rate, percent
T	temperature
V	average velocity at an axial station
v	local velocity at a radial position
X	axial gap between vortex fence and exit of prediffuser (see fig. 3)
Y	radial gap between vortex fence and exit (see fig. 3)

- γ specific-heat ratio
 ϵ diffuser efficiency, eq. (5)
 η diffuser effectiveness, eq. (3)

Subscripts:

- i inner wall
m maximum
o outer wall
r local value at given radial position
t total
0 stagnation condition
1 diffuser inlet station
2 diffuser exit station

APPARATUS AND INSTRUMENTATION

Flow System

The investigation was conducted in the test facility described in reference 4. A schematic of the facility flow system is shown in figure 1. Air, at a pressure of approximately 100 N/cm^2 abs (145 psia) and ambient temperature, is supplied to the facility by a remotely located compressor station. This air feeds the three branches of the flow system.

The center branch (identified as "main air line") provides the airflow through the test diffuser. The air flowing through this branch is metered by a square-edged orifice installed with flange taps according to ASME standards. The air is then throttled to near atmospheric pressure by a flow control valve before entering a mixing chamber from which it flows through the test diffuser. The air discharging from the diffuser is exhausted to the atmosphere through a noise-absorbing duct.

The two other branches of the flow system supply the two air ejectors, which produce the required vacuum for the inner- and outer-wall diffuser bleed flows. The ejectors are designed for a supply air pressure 68 N/cm^2 abs (100 psia) and are capable of producing absolute pressures as low as 2.38 N/cm^2 abs (7.0 in. Hg).

The diffuser inner- and outer-wall bleed flows are also metered by square-edged orifices. These orifices are also installed with flange taps according to ASME

specifications in the suction flow lines that connect diffuser inner - and outer -wall bleed chambers to their respective ejector vacuum sources.

Diffuser Test Apparatus

The diffuser test apparatus used in this investigation was essentially that used in reference 4 but for a few modifications. An axial section of the apparatus is shown in figure 2. As in reference 4 the centerbody that formed the inner annular surface was cantilevered from eight equally spaced support struts located 30 centimeters (12 in.) upstream of the diffuser inlet passage. This construction minimized the possibility of strut flow separation having an undesirable effect on the circumferential profile of inlet velocity.

Diffuser Walls

The removable walls forming the prediffuser passage were positioned as shown in figure 2. The wall geometry and the suction slots formed by the prediffuser walls and the vortex fence are shown in figure 3. The vortex fences on each wall consist of flat metal rings. The radial gap between the trailing edge of the prediffuser and the outer diameter of the vortex fence is referred to as the Y dimension in the figure. This dimension had values of 0.05, 0.1, 0.15, to 0.18 times diffuser inlet height obtained by successive machining.

Both vortex fences were successively positioned at axial locations of 0.1, 0.2, 0.3, 0.4, 0.5, and 0.6 times inlet height from the trailing edge of the prediffuser as indicated by the X dimension in figure 3. To prevent flow separation upstream of the vortex fence, the annular prediffuser was designed with a conservative included divergence angle of 7° resulting in a prediffuser area ratio of 1.15 at a length to inlet height ratio L/H of 1.25. The overall diffuser area ratio was 4.0 with the overall diffuser length as defined by the position of the exit instrumentation set at an L/H of 2, 4, and 6 from the vortex fence. The vortex fences and the upstream walls of the diffuser formed the partially enclosed inner and outer suction chambers.

Diffuser Instrumentation

The essential diffuser instrumentation is indicated in figures 2 and 3. Diffuser inlet total pressure was obtained from three five-point total pressure rakes located at

station 1 and equally spaced around the annular circumference. Inlet static pressure was measured by three wall taps also located at station 1.

Diffuser exit total and static pressures were obtained from three nine-point pitot static rakes that could be rotated in a circumferential direction and translated axially. For this investigation these rakes were positioned downstream of the diffuser inlet plane at a distance equal to twice the inlet passage height. All rake pressures were measured by three Scanivalves, each ducting pressures from a maximum of 48 ports to a flush-mounted, $\pm 6.9 \times 10^3$ pascals (± 1.0 psid), strain-gage transducer. The valve dwell time at each port was 0.2 second, or over three times the interval required to reach steady state. Continuous calibration of the Scanivalve system was provided by ducting known pressures to several ports. Visual display of pressure profiles was made available by also connecting all inlet rakes and two exit rakes to common well manometers using dibutyl phthalate fluid (specific gravity, 1.04). In addition, flow behavior in the diffuser exit passage could also be monitored with tufts.

All other pressure data, such as orifice line pressures for the main air line and the subatmospheric bleed-air lines, were obtained from individual strain-gage pressure transducers. The temperatures of the various flows were measured with copper-constantan thermocouples.

All data were remotely recorded on magnetic tape for subsequent processing with a digital data reduction program. In addition, any test parameter could be displayed in the facility control room by means of a digital voltmeter.

PROCEDURE

Performance Calculations

The overall diffuser performance was evaluated in terms of the radial profile of exit velocity, diffuser effectiveness, total-pressure loss, and diffuser efficiency. The values of the last three quantities or computations were expressed in percentages. Intermediate computations included average static and total pressures, local and average Mach numbers, and local- to average-Mach-number ratios; that is, the equivalent of the local- to average-velocity ratios. The average pressures and Mach numbers at the diffuser exit, P_2 , P_{02} , and M_2 , were computed by trapezoidal integration using area ratio weighted pressures at the various radial positions. At the diffuser inlet straight arithmetic averages were computed. Local Mach numbers for each pitot tube were computed from the compressible flow relation

$$M_r = \sqrt{\frac{2}{\gamma - 1} \left(\frac{p_0}{p} \right)^{(\gamma-1)/\gamma} - 1} \quad (1)$$

where p_0 and p represent the measured local total and static pressures and γ represents the specific heat ratio, set equal to 1.4 for the near ambient conditions of this investigation.

Diffuser and bleed airflow rates were computed from the respective orifice pressures and temperatures. As a check on the arithmetically averaged inlet Mach number, a mean effective inlet Mach number was also computed by iteration from inlet airflow rate, total pressure, temperature, and area data as they relate in the expression:

$$M_1 = \frac{\dot{m}_1}{P_{01} A_1} \sqrt{\frac{RT_{01}}{\gamma g_c}} \left(1 + \frac{\gamma - 1}{2} M_1^2 \right)^{(\gamma+1)/2(\gamma-1)} \quad (2)$$

The velocity ratios at each radial position, needed to generate velocity profiles, were obtained from the circumferential averages of the local- to average-Mach-number ratios. A plotting routine was used to generate the velocity profiles by computer with output on microfilm.

Diffuser effectiveness was computed from the following relation:

$$\eta = \frac{P_2 - P_1}{(P_{01} - P_1) \left[1 - \left(\frac{1 - B}{AR} \right)^2 \right]} \times 100 \quad (3)$$

Equation (3) is an approximation expressing the ratio of actual to ideal conversion of inlet dynamic pressure to exit static pressure for the case of compressible flows through a diffuser with wall bleed for $M \leq 0.5$ and $AR \geq 2$. For the conditions of the present study the use of equation (3) introduced an approximation error of less than 0.6 percent. A derivation of equation (3) and its limitations is shown in reference 7.

The total-pressure loss was defined as

$$\frac{\Delta P_0}{P_{01}} = \frac{P_{01} - P_{02}}{P_{01}} \times 100 \quad (4)$$

Diffuser efficiency was computed from the relation

$$\epsilon = \frac{\left(1 + \frac{\gamma - 1}{2} M_1^2\right) \left(\frac{P_{02}}{P_{01}}\right)^{(\gamma-1)/\gamma} - 1}{\frac{\gamma - 1}{2} M_1^2} \times 100 \quad (5)$$

Equation (5) was derived in reference 7 for the case where the diffuser-exit velocity is negligible. This restriction can be removed from equation (5) (as shown in ref. 7) by making a minor change in the definition and subsequent derivation of the diffuser efficiency parameter. Hence, equation (5) as used in this report, relates the total energy level available at the exit of a diffuser, to the upstream total energy level with the inlet static enthalpy being the reference.

Test Conditions

Typical diffuser inlet conditions were the following:

Total pressure, pascals (psia)	9.86×10^4 to 10.15×10^4 (14.29 to 14.72)
Static pressure, pascals (psia)	9.39×10^4 to 9.88×10^4 (13.62 to 14.32)
Temperature, K ($^{\circ}$ F)	277 to 289 (39 to 60)
Mach number	0.18 to 0.30
Velocity, m/sec (ft/sec)	61 to 101 (199 to 332)
Reynolds number (based on inlet passage height)	2.1×10^5 to 3.6×10^5
Bleed rate, percent of total flow	0 to 18.0

Units

The U.S. Customary System of units was used for primary measurements and calculations. Conversion to SI units (Système International d'Unités) is done for reporting purposes only. In making the conversion, consideration is given to implied accuracy, which may result in rounding off the values expressed in SI units.

RESULTS AND DISCUSSION

The performance of a high area ratio dump diffuser with suction stabilized vortex flow control was evaluated in terms of the following characteristics: radial profiles of velocity at inlet, intermediate and exit planes, including circumferential variations; diffuser effectiveness (i. e. , static pressure recovery); diffuser efficiency; and diffuser total pressure loss. Because of the low airflow availability, the greater part of the data were obtained at a relatively modest nominal inlet Mach number of 0.18. However, a sufficient number of comparative data points were also taken at an inlet Mach number of 0.3 to establish the absence of a significant inlet Mach number effect on the performance parameters evaluated.

The first part of the test program was devoted to determining the vortex fence position and height which would result in the highest diffuser effectiveness and the lowest pressure loss at reasonable suction rates. The geometry chosen from these tests was subsequently evaluated in terms of the aforementioned performance parameters.

Diffuser Vortex Chamber Geometry Screening Tests

The effect of vortex chamber geometry on diffuser performance was evaluated by successively varying the radial gap Y and the axial gap X over the range of values indicated in figure 3. A summary of the results obtained from the screening tests is shown in table I, which lists the diffuser effectiveness and percent total pressure loss values along with the total suction rate required. Figure 4 shows the diffuser best effectiveness values from table I plotted against the axial gap X with the radial gap Y as a parameter. For a radial gap Y equal to 0.15 times inlet height, the best effectiveness values are 87.1 and 88.9 percent for values of the axial gap X , equal to 0.45 and 0.6 times inlet height, respectively. At the value of X equal to 0.6, and Y values of 0.15 and 0.18 the diffuser effectiveness values are increasing with increasing X . However, the diffuser flow at these conditions was unstable and there was an oscillatory region which caused the effectiveness value to vary with time. At values of X equal to 0.45 and Y equal to 0.15, the diffuser flow and effectiveness values were stable with time. These dimensions were chosen for the final geometry as indicated by the asterisk.

The remainder of the report discusses the results obtained with the final vortex chamber geometry. A summary of performance data for this geometry (model 14) and for models 13 and 15 is given in table II.

Radial Profiles of Inlet Velocity Including Circumferential Variations

The profiles of figure 5 were generated by plotting the ratio of local velocity at a radial position to the average velocity at the inlet station. Profiles in three different circumferential planes, as measured by the three equally spaced inlet plane rakes are shown on the right side and the circumferentially average profile is shown on the left side of each figure. Although diffuser effectiveness results are discussed in a later section, circumferential variations in this parameter do reflect variations of inlet static pressure, which are a further indication of the circumferential uniformity of the inlet flow. Hence diffuser effectiveness values for each of the rake positions are shown in figure 5, and a few remarks pertaining to the effect of inlet flow uniformity on diffuser effectiveness are included here.

For the case of no suction (fig. 5(a)), the individual rake profiles show that the circumferential nonuniformity is within ± 2 percent except at the 90 percent span position, where it is about ± 4 percent. Both the individual rake profiles and the circumferentially averaged profile show a mild hub bias which is characteristic of flow in annular passages and discussed in reference 8. Diffuser effectiveness values, computed from individual rake data, are within 5 percent of each other. It is interesting to note that, as the suction rate is raised to 9.9 percent (fig. 5(b)) and 12.3 percent (fig. 5(c)), the circumferentially averaged radial profile remains essentially unchanged, but the circumferential nonuniformity of the profiles, still about ± 4 percent at 9.9 percent suction, suddenly deteriorates to approximately ± 10 percent at the 12.3 percent total suction rate (fig. 5(c)). Also, the diffuser effectiveness values computed from individual rake data, while significantly higher than those obtained without suction, deviate from each other by over 14 percent. Furthermore, the effectiveness value for the 'rake 2' position and the average effectiveness are seen to actually decrease as the suction rate is increased from 9.9 to 12.3 percent. This indicates that a separated flow region is established downstream of 'rake 2' and that this region grows with increasing suction rate until it causes a decrease of the diffuser inlet flow in the 'rake 2' sector. Hence, contrary to experience with other diffuser geometries (refs. 7 and 9), a limiting suction rate exists with the particular vortex flow diffuser discussed here, beyond which performance deteriorates. This limiting suction rate was found to be about 10 ± 1.0 percent for the best conditions of this investigation.

Radial Profiles of Velocity at Prediffuser Exit Station

Since the standard diffuser rig instrumentation did not include pitot rakes at the prediffuser exit plane, velocity profiles in this plane were determined by use of a traversing pitot static probe. Figure 6(a) shows the profile without suction to be almost identical to

the previously discussed radial profiles at the inlet plane. This confirms that the pre-diffuser is passing flow attached to both the inner and the outer walls and that no flow separation occurs upstream of the prediffuser trailing edge. But where the average radial profile at the inlet plane was only mildly affected by suction, the radial profile at the prediffuser exit plane can become significantly hub peaked as shown in 6(b) or significantly tip peaked as shown in figure 6(c) depending on the distribution of suction rate applied to the inner or outer vortex chambers.

Radial Profiles of Exit Velocity

General observations. - The following figures will illustrate the hysteresis effect of velocity distribution after the removal of suction. The radial profiles of exit velocity are shown in figures 7(a) and (b) for a nominal inlet Mach number of 0.18 and for exit rakes positioned at an $L/H = 6$.

Figure 7(a) shows the hub biased radial profiles of exit velocity obtained by applying some suction to the inner wall vortex chamber prior to data recording. The suction rate was then set to zero while the profile data were recorded. The three rake profiles circumferentially spaced at 120° intervals in the diffuser exit plane had a maximum circumferential nonuniformity of about ± 30 percent of the average velocity at the midspan position. Figure 7(b) shows the individual rake profiles obtained by applying suction to the outer vortex chamber prior to data recording but prohibiting any suction during the recording of pitot-static probe data. The tip peaked profiles obtained in this case together with the hub peaked profiles obtained previously confirm that there is hysteresis or "memory" generated in the flow by the toroidal vortex. Either hub peaked or tip peaked profiles can be generated by momentary application of suction on the inner or the outer vortex chamber, respectively. Figure 8 shows this hysteresis effect also exists with a medium suction rate of approximately 6.2 percent maintained during data recording. About 40 percent of the total suction is applied on the inner and 60 percent on the outer wall. The hub peaked profiles of figure 8(a) resulted when the outer wall suction was momentarily interrupted prior to data recording, while the tip peaked profiles of figure 8(b) occurred when the inner wall suction was momentarily stopped prior to data recording but reestablished during the recording phase. At a high suction rate (11.2 percent total suction), the circumferential flow field is no longer biased toward either wall as a whole but is divided into a number of regions within each of which the flow may be hub or tip biased or even periodically oscillate between the two extremes in a quasi-stable fashion. Evidence of such a circumferentially segmented flow is shown in figure 9(a). Note that the averaged flow profile of figure 9(b) does not represent the circumferential flow field. Circumferential surveys are needed to reveal the flow field in this case. Such survey results are discussed in the next section.

Circumferential variation of exit velocity profiles. - The circumferential variation in exit velocity profiles was determined by sweeping the annular exhaust passage and recording profile data at 10° increments. In an effort to present the results of these surveys in a compact fashion polar plots are presented in figures 10 and 11 showing the variation of local- to average-velocity ratios for the 10 and 90 percent span position over the full 360° annular circumference. The flow map shown in figure 10 was obtained at a total suction rate of 6.2 percent but it is typical of maps obtained at up to 9.5 percent suction rate. Hub peaked velocity profiles throughout the annular circumference are indicated by the velocity ratio values for the 10 percent span location ranging from 1.5 to 2.5. Outer wall separation is indicated by the low and zero velocity ratio values for the 90 percent passage height position.

Figure 11(a) shows a circumferentially segmented flow obtained at a total suction rate of 10.2 percent. The flow field no longer has uniformly hub peaked or tip peaked velocity profiles but is divided into sectors containing flow with inner wall attachment (hub peaked), outer wall attachment (tip peaked), and flow attached to both walls. Adjacent to a narrow slice of tip attachment (10° to 20°), there is a large sector extending from 30° to 120° containing flow with hub attachment. From 130° to 140° there is a narrow region of tip attachment adjacent to flow separated from both walls (140° to 160°). Flow is attached to both walls from 160° to 180° , and from 180° to 270° the flow becomes increasingly tip peaked. From 280° to 360° the flow is again attached to both walls. Of these flow patterns encountered during the circumferential surveys the hub peaked profiles were most stable while flows attached to both walls were unstable, undergoing random undulations to tip and hub attachment. This unsteady flow behavior can also be inferred from the irregular shape of the midspan velocity ratio circumferential plot shown in figure 11(b).

Effect of exit rake position on radial profiles of exit velocity. - To verify that the previously discussed exit profiles obtained at an $L/H = 6$ position were fully developed, radial profiles of exit velocity were also measured at $L/H = 2$ and $L/H = 4$ positions. Inlet conditions were held constant. The characteristic exit velocity profiles as determined by the three nine-point pitot-static rakes are shown in figure 12 for the case of no suction and in figure 13 for a nominal suction rate of eight percent, with approximately three percent applied on the inner wall and five percent on the outer wall. The inlet profiles are also shown for reference for each case. The typical annular jet flow profile shown in figure 12(a) indicates that the flow is separated from both walls at the $L/H = 2$ position when no suction is applied to the vortex chambers. At an $L/H = 4$, figure 12(b), the flow has become attached to the inner wall as evidenced by the strongly hub biased profile, which continues with only slight further development in the downstream direction as indicated by figure 12(c), showing the exit profile at the $L/H = 6$ position. In contrast to the "no suction" case depicted in figure 12, the flow, although still separated from both walls, is beginning to turn toward the inner wall at a position as close as

$L/H = 2$ downstream of the vortex fences, when about 8 percent suction is applied to the vortex chambers, as shown in figure 13(a). Figures 13(b) and (c) show that the flow undergoes additional hub biasing as it proceeds downstream. However, the change in exit velocity profile is smaller between the $L/H = 4$ and $L/H = 6$ diffuser exit stations than it is between the $L/H = 2$ and $L/H = 4$ stations. This may be explained by considering that at the $L/H = 2$ station the flow is radially inward and not yet parallel to the walls of the diffuser exit passage. Consequently, the flow streamlines are not aligned with the pitot-static tubes and the pressure measurements may therefore not be valid at all radial span positions across the diffuser exit passage. The flow does appear to be developed (i. e. , parallel to the exit passage) at the $L/H = 4$ station.

A comparison of profiles with suction (fig. 13) and without suction (fig. 12) shows that the profiles are flatter with suction at all downstream stations, a fact that is obviously attributable to the more effective flow spreading achieved with the suction stabilized vortices.

Effect of Inlet Mach Number on Radial Profiles of Velocity

A comparison of inlet and exit velocity profiles for nominal inlet Mach numbers of 0.18 and 0.3 is shown for the case of no suction in figure 14 and for a nominal total suction rate of 9.3 percent in figure 15. Both the inlet and the exit profiles shown plotted in these figures were obtained by circumferentially averaging the results obtained from the previously mentioned pitot-static rakes. Agreement between the circumferentially spaced rakes was within ± 4 percent for the inlet profiles and ± 30 percent for the exit profiles.

As shown in figure 14 for the case of no suction, and in figure 15 for a nominal suction of 9.3 percent, inlet Mach number has no effect on either inlet or exit radial profiles. The inlet profiles shown in both figures 14 and 15 consistently show the same characteristic form discussed previously. Hence it may be concluded that the inlet profiles are not affected by inlet Mach number.

Regarding the radial profiles of exit velocity a comparison of profiles shown in figure 14 for the no suction case and 15 for a nominal suction rate of 9.3 percent shows that the radial profile of exit velocity also is unaffected by inlet Mach number as long as the suction rate is kept constant on each wall vortex chamber.

Diffuser Effectiveness

Diffuser effectiveness, as defined by equation (3), expresses the ratio of actual to ideal conversion of dynamic inlet pressure to exit static pressure at a reduced velocity. The effect of suction rate on diffuser effectiveness is shown in figure 16 for the three different downstream stations and the two inlet Mach numbers investigated. The diffuser

effectiveness for all three exit rake locations is seen to increase according to sigmoid relations with suction rate. Although the effectiveness is seen to be independent of inlet Mach number, it does increase with exit rake position with most of the increase occurring as the exit rakes are moved from the $L/H = 2$ to $L/H = 4$ position. This corroborates the previously discussed observations regarding the effect of exit rake position on radial profiles of velocity. On the basis of those observations it was also concluded that most of the flow development occurs upstream of the $L/H = 4$ position with little change downstream. At the $L/H = 6$ position the cubic relation between diffuser effectiveness and suction rate may be approximately expressed by the equation

$$\eta = 40.0 + 0.6S_t + S_t^2 - 0.06S_t^3 \quad (6)$$

where η is the diffuser effectiveness and S_t is the total suction rate with the values of both parameters expressed in percent. Similarly the effectiveness at the $L/H = 4$ position may be approximated by

$$\eta = 38 + 0.5S_t + S_t^2 - 0.06S_t^3 \quad (7)$$

Equations (6) and (7) correlate the results for total suction rates ranging from zero to 13 percent.

Although the general sigmoid shape of the curves represented by equations (6) and (7) bears a superficial resemblance to the performance characteristic curve determined in reference 6, some of the performance trends observed in this study were found to differ significantly from those reported in that reference. In reference 6 the curve representing the relation between diffuser effectiveness and suction rate was postulated to consist of three regions:

(1) A weak vortex region characterized by only a slight increase in effectiveness with suction rate. This region was found to extend from zero to about 5.8 percent total suction rate.

(2) A vortex transition region showing an abrupt increase in diffuser effectiveness to over 95 percent as the total suction rate was increased from 5.8 to 6.2 percent.

(3) An established vortex region, beyond 6.2 percent suction, where diffuser effectiveness again increases gradually with suction.

Performance results obtained in this study show less clearly defined boundaries between regions than those observed in reference 6. As can be seen in the lower part of the sigmoid curves of figure 15 the increase in slope is so gradual that the demarcation between regions 1 and 2 is arbitrarily placed at the midpoint of a band extending from about 2 to 4 percent total suction rate. Diffuser effectiveness for the $L/H = 6$ station changes from 40 to 53 percent as the total suction rate is raised from zero to 4 percent. Region 2, extending from about 3 percent to somewhere between 10 and 11 percent, say 10.5

percent, is about an order of magnitude wider than determined in reference 6. Diffuser effectiveness rises from 53 to 87 percent for the downstream measuring station. The peak effectiveness value is somewhat below the 95 percent figure indicated in reference 6.

The most striking contradiction between performance trends observed in this study and those reported in reference 6 arises from a comparison of results obtained in region 3. In this study, region 3, extending beyond 11 percent total suction, was characterized by circumferentially nonuniform, oscillating flow which caused considerable data scatter in the diffuser effectiveness results. However the average trend in this region is an actual decrease in diffuser effectiveness with increasing suction rate, whereas reference 6 reported a continued, albeit gradual, increase in static pressure recovery. The reason for this discrepancy must be ascribed, at least partly, to the circumferentially nonuniform flow behavior the effect of which on diffuser performance was not evaluated in reference 6.

Circumferential Variations in Diffuser Effectiveness

During the circumferential surveys of exit velocity profiles sufficient static pressure profile data were obtained to also permit the determination of local diffuser effectiveness values at each of the circumferential sweep positions of the diffuser exit pitot-static rakes. Analysis of such local diffuser effectiveness results shows that circumferential variations in diffuser effectiveness are negligible, being within 5 percent, for total suction rates less than 10 percent, that is, for operation in regions 1 and 2. For total suction rates in excess of about 11 percent, that is, for operation in region 3, the circumferential variation in diffuser effectiveness becomes significant. A typical circumferential survey of diffuser effectiveness for a total suction rate of 12.3 percent is shown in figure 17. Diffuser effectiveness is seen to vary from about 77 percent at the 190° position to about 87 percent at the 260° position. It is also obvious that the diffuser effectiveness and consequently the static pressure recovery is below average for the annular quadrant extending from the 160° to the 250° position. Regarding the results plotted in figure 17, the reader is reminded that because of instrumentation limitations the circumferential surveys were conducted in the diffuser exit plane ($L/H = 6$ position) only, and no such surveys were made in the inlet plane. Hence the local effectiveness values are based on an inlet static pressures which is the average of the three equally spaced inlet static pressure readings and the circumferential variation in diffuser effectiveness reflects a circumferential variation in local exit static pressure.

Even though full circumferential survey data on inlet static pressure distribution are not available, it is still possible to assess the combined effect of inlet and exit static pressure variations on diffuser effectiveness by comparing results in the three circumferential locations where inlet station instrumentation was provided. Such results,

showing the variation in diffuser effectiveness with the circumferential position of inlet and exit rakes, are given in figure 18 for each of four suction rates. Circumferential variations are seen to be within 6 percent for suction rates below 10 percent, but these variations become more drastic and unpredictable for suction rates above 10 percent. At a suction rate of 12.12 percent (square symbols), for example, diffuser effectiveness was found to vary from about 83.5 percent for position 1 to 72 percent for position 2 and 86.2 percent for position 3. At 12.5 percent suction (triangular symbols) effectiveness values of 83, 92.6, and 88 percent were determined for rake positions 1, 2, and 3, respectively. A second set of data obtained at a nominal 12.5 percent suction (diamond shaped symbols) shows a less drastic variation at a different instant in time.

In light of these results it becomes reasonable to explain the apparent discrepancy between performance results obtained in this study and in reference 6 in terms of circumferential variations.

Diffuser Total Pressure Loss

The decrease in diffuser total pressure loss with total suction rate is shown in figure 19 for the three previously mentioned downstream stations and the two inlet Mach number conditions. As expected, the total pressure loss data also fall on a sigmoid curve (inverted in this case) which again exhibits the three regimes of operation with roughly the same boundaries found in the diffuser effectiveness results. Thus the region of gradual decrease in total pressure loss from zero to 4 percent suction is followed by a region of more rapid decrease as the total suction rate is raised from 4 to about 11 percent beyond which a slight increase in total pressure loss is detected. The lowest values of total pressure loss for a given suction rate were obtained for the $L/H = 6$ position, where the misalignment between radially diverging flow stream lines and the exit total pressure tubes was less severe than at the $L/H = 2$ and $L/H = 4$ positions. The effect of such misalignment is to cause the measured exit total pressures to be in error on the low side and consequently the computed total pressure loss values will be in error on the high side. The magnitude of this error is seen to be more pronounced at high suction rate and high inlet Mach number. For example, at an inlet Mach number of 0.3 and a total suction rate of 10.3 percent, the total pressure loss is seen to be about 1.04 percent for the $L/H = 6$ position and 1.68 percent for the $L/H = 4$ position. This rather large error suggests that reliable total pressure measurements in a diffuser of this type should be made at positions downstream of the vortex rings equal to at least six times inlet height.

Comparison of total pressure loss results obtained at inlet Mach numbers of 0.18 and 0.3 confirms that total pressure loss increases as the square of the inlet Mach number, or, for constant inlet pressure and temperature, as the square of the diffuser mass

flowrate. Since the diffuser mass flowrate for a given set of inlet conditions decreases with increasing suction rate, a part of the total pressure loss decrease obtained with suction must be attributed to the decreased mass flowrate with the remainder being due to decreased wall separation.

To ascertain the relative importance of these two effects, consider that without suction at an inlet Mach number of 0.18 the total pressure loss is 1.2 percent at the $L/H = 6$ position. At a suction rate of 10 percent the total pressure loss is about 0.44 percent yielding a reduction of 0.76 percent. Of this reduction the amount due to reduced mass flowrate is $1.2 \times (1.0 - (1.0 - 0.10)^2) = 0.23$ percent. Hence about 30 percent of the total pressure loss reduction is due to reduced mass flow and 70 percent is due to reduced wall separation losses.

Diffuser Efficiency

The isentropic diffuser efficiency as defined by equation (5) is a measure of the conservation of total enthalpy between the diffuser inlet and exit stations. The relation between diffuser efficiency and diffuser total pressure loss is discussed in reference 7. Values of diffuser efficiency for the tests conducted with the final vortex chamber geometry are given in table II.

Combustor Design Aspects of Some Test Results

Performance results obtained from tests of the annular suction stabilized vortex diffuser contain both positive and negative implications for gas turbine combustor design. The attainment of a diffuser effectiveness, that is, static pressure recovery, as high as 87 percent at a suction rate of 10 percent must certainly be regarded as a positive result. Furthermore, the fact that diffuser effectiveness slightly decreases beyond 10.5 percent suction should not be a serious detriment since it is not likely that an engine cycle could allow much more than 10 percent bleed without significant sacrifice of thermal efficiency. A negative result is the significant decay of circumferential uniformity of radial profiles of exit velocity at a suction rate of 10 percent or more. There is some hope, however, that this problem may not be as severe in a combustor application since the combustor blockage in the diffuser exit passage may be expected to cause some redistribution and stabilization of the flow. The final answer will have to be obtained from combined diffuser combustor tests.

Diffuser bleed schemes aimed at controlling combustor inlet velocity profile, as discussed, for example, in reference 10, may also capitalize on the hysteresis or "flow memory" obtained with the vortex diffuser. Because of this phenomenon it would be

possible to alter the radial profile of combustor inlet velocity from hub biased to tip biased merely by momentary application of outer wall suction. Alternately, the process could be reversed by momentary application of inner wall suction. In this manner combustor airflow distribution could be controlled to suit the requirement of particular operating conditions without continuous application of bleed and therefore without sacrificing any cycle efficiency.

SUMMARY OF RESULTS

The performance of a short annular suction-stabilized-vortex diffuser with variable chamber geometry was evaluated in terms of diffuser velocity profiles, diffuser effectiveness and total pressure loss for nominal inlet Mach numbers of 0.18 and 0.3. The test program consisted of a vortex-chamber-geometry screening phase followed by detailed performance evaluation of the optimum chamber geometry. The results were as follows:

1. The best chamber geometry had inner and outer wall suction slots with radial gaps of 0.15 and axial gaps of 0.45 times inlet height.
2. Diffuser effectiveness was found to increase according to a sigmoid curve from 40 percent without suction to 87 percent at 10.5 percent suction at the $L/H = 6$ exit station and was found to decrease gradually above a suction rate of 11 percent.
3. Diffuser total pressure loss at an inlet Mach number of 0.30 decreased from 3.15 percent without suction to 1.1 percent at a total suction rate of 10 percent.
4. At suction rates below 9 percent, with about 40 percent of the total suction applied on the inner wall and 60 percent on the outer wall, either hub biased or tip biased radial profiles were maintained, depending on the profile existing without suction.
5. Radial profiles of exit velocity were invariant with inlet Mach number but they did change with suction rate. Radial profiles of exit velocity could be made hub peaked by momentary application of inner wall suction and tip peaked by momentary application of outer wall suction.
6. Circumferential uniformity of radial profiles of inlet velocity deteriorated significantly as the total suction rate was increased above 10 percent. For example, while such uniformity was within ± 4 percent for suction rates ranging from 0 to 9.9 percent, it deteriorated to ± 10 percent for a total suction rate of 12.3 percent.
7. Above a total suction rate of 10 percent the radial profiles of exit velocity became circumferentially nonuniform, made up of sectors containing hub peaked, tip peaked, and unstable profiles.

Lewis Research Center,
National Aeronautics and Space Administration,
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505-04.

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TABLE I. - EFFECT OF SUCTION CHAMBER GEOMETRY

ON DIFFUSER PERFORMANCE

[Exit rake position $L/H = 6.$]

Model	Axial gap, X	Radial gap, Y	Inlet Mach number, M_1	Diffuser effectiveness, η , percent	Total pressure loss, $\Delta P/P$, percent	Suction rate, percent
1	0.10	0.05	0.182	64.7	0.94	9.62
2	.15	↓	.184	77.8	.66	17.1
3	.20		.184	83.4	.52	14.13
4	.25		.188	83.4	.53	15.1
5	.30		.185	84.5	.46	19.0
6	0.15	0.10	0.184	83.2	0.52	14.3
7	.20	↓	.185	85.1	.51	12.1
8	.25		.184	84.8	.47	12.4
9	.30		.183	84.7	.51	12.0
10	.40		.184	84.5	.46	14.1
11	0.20	0.15	0.183	83.1	0.53	14.1
12	.30	↓	.183	86.3	.51	12.5
13	.40		.182	86.7	.53	10.33
14	.45		^a .182	^a 87.1	^a .45	^a 10.31
15	.60		.183	88.9	.39	11.6
16	0.40	0.18	0.182	84.9	0.49	13.0
17	.50	↓	.183	86.3	.52	12.7
18	.60		.183	88.3	.38	11.0
19	^b .2		.181	84.4	.47	14.7
	^c .5					

^aFinal geometry chosen.^bInner.^cOuter.

TABLE II. - DIFFUSER PERFORMANCE DATA

(a) $X = 0.4$; $Y = 0.15$; model 13

Reading number	Diffuser inlet Mach number	Airflow		Inlet pressure				Inlet total temperature		Suction rate, percent			Diffuser effectiveness, η , percent	Diffuser efficiency, ϵ , percent	Total pressure loss, $\Delta P/P$, percent	Exit rake position, L/H
		kg/sec	lbm/sec	Total		Static		K	°F	Inner wall	Outer wall	Total				
				N/cm ²	psia	N/cm ²	psia									
1051	0.184	2.26	4.98	9.94	14.42	9.70	14.06	284	51	0	0	0	38.58	47.02	1.24	6
1052	.182	2.23	4.92	9.93	14.41	9.70	14.06	↓	↓	0	0	0	39.01	47.57	1.20	↓
1053	.183	2.24	4.94	9.91	14.38	9.67	14.03	↓	↓	1.37	2.84	4.21	54.69	59.16	.95	↓
1054	.183	2.23	4.92	9.90	14.36	9.66	14.01	↓	↓	2.53	3.74	6.27	60.82	62.78	.86	↓
1055	.182	2.22	4.90	9.88	14.33	9.65	13.99	↓	↓	2.88	4.59	7.47	70.81	69.78	.69	↓
1056	0.183	2.23	4.92	9.87	14.32	9.64	13.98	284	51	3.00	4.50	7.50	76.60	74.37	0.60	6
1057	.183	2.23	4.92	9.87	14.31	9.63	13.97	↓	↓	2.97	4.49	7.46	77.26	74.94	.58	↓
1058	.182	2.22	4.90	9.88	14.33	9.65	13.99	↓	↓	2.98	4.54	7.52	70.05	70.01	.69	↓
1059	.184	2.24	4.94	9.86	14.30	9.62	13.95	↓	↓	4.02	6.17	10.18	85.89	80.25	.46	↓
1060	.184	2.24	4.93	9.86	14.30	9.62	13.95	↓	↓	3.90	6.35	10.25	87.73	80.68	.45	↓
1061	0.184	2.24	4.93	9.86	14.29	9.62	13.95	284	51	6.01	6.69	12.70	86.66	82.06	0.42	6
1062	.184	2.24	4.93	↓	14.30	9.64	13.98	↓	↓	5.28	7.06	12.34	81.25	77.71	.52	↓
1063	.184	2.23	4.93	↓	14.29	9.62	13.95	↓	↓	7.87	6.75	14.62	85.05	80.84	.45	↓
1064	.183	2.23	4.91	↓	14.30	9.63	13.97	↓	↓	3.51	5.69	9.20	81.92	78.45	.50	↓
1065	.182	2.21	4.88	↓	14.31	9.64	13.97	↓	↓	3.41	5.71	9.12	80.57	77.38	.52	↓
1066	0.184	2.29	5.04	10.02	14.53	9.77	14.17	281	46	0	0	0	38.73	46.65	1.25	6
1067	.183	2.27	5.01	10.01	14.52	9.76	14.16	282	47	↓	1.33	1.33	43.39	49.87	1.16	↓
1068	.182	2.26	4.99	10.01	14.51	9.77	14.16	↓	47	↓	1.35	1.35	40.76	51.17	1.12	↓
1069	.183	2.27	5.00	10.00	14.50	9.76	14.16	↓	48	↓	1.30	1.30	45.69	51.76	1.12	↓
1070	.182	2.26	4.98	10.01	14.52	9.77	14.17	↓	48	↓	1.93	1.93	46.92	52.73	1.09	↓
1071	0.182	2.26	4.98	10.00	14.51	9.76	14.16	282	48	0	1.86	1.86	48.00	53.22	1.08	6
1072	.183	2.27	5.00	↓	14.50	↓	14.15	↓	↓	1.24	2.66	3.89	52.65	57.42	.99	↓
1073	.182	2.26	4.97	↓	14.50	↓	14.15	↓	↓	1.49	2.69	4.17	52.03	54.85	1.03	↓
1074	.183	2.26	4.99	↓	14.50	↓	14.15	↓	↓	1.71	3.19	4.90	56.00	60.47	.91	↓
1075	.182	2.25	4.97	9.99	14.49	9.75	14.14	↓	↓	1.87	3.58	5.45	60.66	63.21	.85	↓
1076	0.183	2.27	5.00	9.99	14.49	9.75	14.14	282	48	1.98	3.57	5.55	56.54	59.05	0.95	6
1077	.183	2.26	4.98	9.99	14.49	9.75	14.14	↓	↓	2.41	3.67	6.08	61.58	62.57	.86	↓
1078	.183	2.27	5.00	9.99	14.49	9.75	14.14	↓	↓	2.56	4.10	6.66	64.84	65.59	.80	↓
1079	.182	2.25	4.97	9.98	14.48	9.75	14.13	↓	↓	2.66	4.17	6.82	65.83	66.36	.77	↓
1080	.184	2.27	5.01	9.98	14.48	9.74	14.13	↓	↓	2.62	4.31	6.93	69.17	69.17	.72	↓
1081	0.182	2.25	4.97	9.99	14.49	9.75	14.14	282	48	2.68	4.35	7.03	64.75	65.30	0.80	6
1082	.182	2.25	4.97	9.98	14.47	9.74	14.13	↓	↓	2.80	4.45	7.25	68.91	68.34	.73	↓
1083	.183	2.26	4.99	9.98	14.47	9.74	14.13	↓	↓	2.75	4.50	7.25	69.92	69.62	.70	↓
1084	.182	2.25	4.97	9.98	14.47	9.74	14.13	↓	↓	2.86	4.75	7.60	74.14	72.58	.63	↓
1085	.182	2.25	4.97	9.99	14.49	9.75	14.14	↓	↓	2.83	4.72	7.54	66.87	66.12	.78	↓
1086	0.183	2.26	4.98	9.99	14.48	9.75	14.14	282	48	2.93	5.27	8.20	69.17	68.54	0.73	6
1087	.182	2.25	4.96	9.97	14.46	9.73	14.12	↓	↓	2.94	5.29	8.23	80.58	75.66	.56	↓
1088	↓	↓	4.96	9.97	14.46	9.74	14.12	↓	↓	2.95	5.28	8.23	80.89	75.52	.56	↓
1089	↓	↓	4.97	9.97	14.45	9.73	14.11	↓	↓	3.52	5.60	9.12	82.95	75.97	.55	↓
1090	↓	↓	4.96	9.96	14.45	9.73	14.11	↓	↓	3.70	5.83	9.53	82.55	75.44	.57	↓
1091	0.183	2.26	4.98	9.96	14.45	9.73	14.11	282	48	3.67	5.78	9.45	83.06	77.32	0.53	6
1092	.182	2.25	4.97	9.96	↓	9.72	14.10	↓	↓	3.96	6.37	10.33	86.67	76.85	.53	↓
1093	.183	2.26	4.98	9.97	↓	9.73	14.11	↓	↓	4.32	5.77	10.09	81.91	76.67	.54	↓
1094	.183	2.26	4.97	9.96	↓	9.73	14.11	↓	↓	4.59	7.13	11.72	83.17	77.15	.53	↓
1095	.183	2.26	4.98	9.96	↓	9.73	14.11	↓	↓	4.65	6.65	11.30	87.98	83.10	.39	↓
1096	0.183	2.26	4.99	9.96	14.45	9.73	14.11	282	48	4.66	6.57	11.23	86.10	82.15	0.42	6
1097	.183	2.26	4.99	9.96	14.45	9.72	14.10	282	48	4.68	6.62	11.30	87.55	82.50	.41	6
1098	.182	2.25	4.96	9.96	14.45	9.73	14.11	282	48	5.91	6.61	12.52	87.95	84.92	.35	6

TABLE II. - Continued.

(b) X = 0.45; Y = 0.15; model 14

Reading number	Diffuser inlet Mach number	Airflow		Inlet pressure				Inlet total temperature		Suction rate, percent			Diffuser effectiveness, η , percent	Diffuser efficiency, ϵ , percent	Total pressure loss, $\Delta P/P$, percent	Exit rake position, L/H
		kg/sec	lbm/sec	Total		Static		K	°F	Inner wall	Outer wall	Total				
				N/cm ²	psia	N/cm ²	psia									
1099	0.179	2.25	4.95	10.12	14.67	9.88	14.32	280	45	0	0	0	39.23	45.49	1.20	6
1100	.182	2.29	5.04	10.11	14.67	9.87	14.31	282	48	0	1.25	1.25	44.08	50.00	1.15	↓
1101	.181	2.27	5.01	10.11	14.66	9.86	14.31	↓	↓	0.97	2.03	3.00	48.42	53.74	1.05	
1102	.181	2.27	5.01	10.10	14.65	9.86	14.30			0	1.99	1.99	48.46	52.78	1.08	
1103	.181	2.26	4.99	10.09	14.63	9.85	14.28			0	3.05	3.05	57.61	61.03	.88	
1104	0.180	2.25	4.96	10.08	14.62	9.84	14.28	282	48	1.41	3.05	4.46	57.28	59.50	0.91	6
1105	.180	2.25	4.95	10.07	14.61	9.83	14.26	↓	↓	2.47	3.79	6.26	61.06	62.52	.84	↓
1106	.181	2.26	4.98	10.07	14.61	9.83	14.26			2.46	3.74	6.20	61.65	62.39	.85	
1107	.182	2.26	4.99	10.06	14.59	9.81	14.23			2.72	4.40	7.12	70.80	69.40	.70	
1108	.181	2.26	4.99	10.05	14.58	9.81	14.23			2.73	4.42	7.15	70.84	70.77	.67	
1109	0.182	2.27	5.00	10.06	14.59	9.82	14.24	282	48	2.72	4.35	7.07	65.60	65.23	0.80	6
1110	.182	2.27	5.00	10.04	14.56	9.80	14.21	↓	↓	3.19	5.23	8.42	79.97	76.47	.54	↓
1111	.181	2.26	4.98	↓	↓	↓	14.22			3.25	5.06	8.31	77.43	74.60	.58	
1112	.182	2.27	5.01				14.21			3.56	5.60	9.16	81.83	78.11	.51	
1113	.182	2.26	4.98				↓			↓	↓	14.21	3.61	5.59	9.20	
1114	0.183	2.27	5.01	10.03	14.54	9.79	14.20	282	47	3.98	6.32	10.31	87.14	86.43	0.45	6
1115	.182	2.26	4.99	10.02	↓	↓	14.19	↓	↓	3.90	6.20	10.09	86.63	80.83	.44	↓
1116	↓	2.26	4.99	10.02			14.20			4.68	6.58	11.26	85.41	80.54	.45	
1117		2.27	5.00	10.02			14.20			4.65	6.53	11.17	87.03	81.46	.43	
1118		2.26	4.99	10.03			14.19			5.98	6.46	12.44	86.16	80.44	.45	
1119	0.182	2.27	5.00	10.02	14.54	9.79	14.19	282	47	5.93	6.47	12.40	84.98	80.55	0.45	6
1120	.183	2.27	5.01	10.02	14.54	9.79	14.19	↓	↓	7.14	6.97	14.12	86.88	81.00	.44	↓
1121	.183	2.28	5.03	10.03	14.55	9.79	14.21			7.02	6.89	13.91	83.72	78.93	.49	
1122	.184	2.28	5.03	10.03	14.54	9.79	14.20			7.20	6.79	14.00	87.60	83.35	.39	
1123	.183	2.27	5.01	10.03	14.54	9.79	14.20			10.66	6.73	17.39	85.16	82.00	.42	
1124	0.305	3.71	8.17	10.15	14.72	9.49	13.76	282	47	3.70	5.64	9.34	81.84	79.53	1.30	6
1125	.304	3.69	8.14	10.15	14.72	9.49	13.76	281	46	3.71	5.66	9.37	81.82	79.98	1.26	↓
1126	.305	3.70	8.16	10.12	14.68	9.46	13.73	↓	↓	4.30	6.37	10.67	86.86	83.69	1.04	
1127	.305	3.69	8.15	10.12	14.68	9.46	13.73			4.31	6.40	10.71	86.62	83.70	1.04	
1128	.221	2.81	6.19	10.35	15.01	9.69	14.06			0	0	0	39.87	5.61	3.15	
1235	0.183	2.30	5.07	10.04	14.56	9.79	14.21	277	38	0	0	0	34.87	48.20	1.20	2
1236	.182	2.28	5.02	10.02	14.54	9.79	14.20	277	39	0	1.42	1.42	39.73	52.30	1.09	↓
1237	.183	2.28	5.03	10.01	14.52	9.77	14.17	278	40	1.37	2.73	4.10	48.20	57.93	.97	
1238	.184	2.30	5.07	10.00	14.50	9.75	14.15	278	40	2.42	3.68	6.10	58.29	64.96	.82	
1239	.183	2.29	5.04	9.98	14.48	9.74	14.13	278	40	2.71	4.30	7.01	64.29	69.35	.72	
1240	0.183	2.28	5.03	9.97	14.47	9.73	14.12	278	40	3.08	4.73	7.90	68.82	73.01	0.63	2
1241	.182	2.27	5.00	9.96	14.45	9.72	14.10	278	40	3.47	5.51	8.98	72.77	75.47	.56	↓
1242	.184	2.29	5.04	9.96	14.45	9.72	14.10	278	40	3.86	6.05	9.91	75.78	78.56	.50	
1243	.183	2.28	5.03	9.97	14.46	9.73	14.11	277	39	4.55	5.43	9.98	73.11	75.45	.57	
1244	.184	2.28	5.04	9.95	14.43	9.71	14.09	277	39	4.66	6.44	11.10	77.26	78.32	.51	
1245	0.183	2.28	5.03	9.96	14.44	9.72	14.10	277	39	5.93	6.35	12.28	76.89	78.12	0.51	2
1246	.184	2.29	5.05	9.95	14.43	9.72	14.10	↓	↓	5.56	8.50	14.06	78.20	76.60	.55	↓
1247	.184	2.28	5.04	9.95	14.43	9.71	14.09			7.78	7.07	14.85	79.21	76.38	.55	
1248	.225	2.80	6.18	10.06	14.59	9.39	13.62			5.61	8.33	13.94	76.07	59.94	1.40	
1249	.182	2.28	5.03	10.05	14.58	9.81	14.23			278	40	0	0	0	38.54	
1250	0.181	2.28	5.02	10.04	14.57	9.81	14.22	278	40	0	1.20	1.20	42.61	52.27	1.09	4
1251	.182	2.28	5.03	10.03	14.55	9.80	14.21	↓	↓	1.34	2.68	4.01	52.63	60.16	.92	↓
1252	.183	2.28	5.02	9.99	14.50	9.76	14.15			2.99	4.81	7.80	72.81	75.18	.57	
1253	.183	2.28	5.04	9.97	14.47	9.74	14.13			3.90	5.92	9.82	81.10	81.36	.44	
1254	.183	2.28	5.02	9.97	14.46	9.74	14.12			4.63	6.46	11.09	83.92	82.66	.40	
1255	0.183	2.28	5.03	9.98	14.47	9.74	14.12	278	40	5.82	6.32	12.14	82.28	82.26	0.41	4
1256	.183	2.28	5.02	9.98	14.47	9.74	14.13	↓	↓	6.35	6.68	13.04	84.09	74.34	.60	↓
1257	.183	2.28	5.03	9.97	14.47	9.74	14.12			6.33	6.71	13.04	84.63	75.08	.58	
1258	.307	3.73	8.22	10.08	14.62	9.42	13.66			4.24	6.17	10.41	81.46	73.60	1.70	
1259	.308	3.74	8.24	10.08	14.62	9.41	13.65			4.21	6.14	10.35	81.52	73.48	1.71	
1260	0.307	3.74	8.23	10.09	14.63	9.42	13.66	278	40	3.75	6.23	9.98	80.43	75.07	1.61	4
1261	.307	3.73	8.21	10.07	14.61	9.41	13.64	278	40	3.73	6.28	10.01	82.64	73.97	1.67	4
1262	.300	3.74	8.24	10.31	14.96	9.65	13.99	278	40	0	0	0	38.18	46.21	3.29	4

Table II. - Concluded.

(c) $X = 0.60$; $Y = 0.15$; model 15

Reading number	Diffuser inlet Mach number	Airflow		Inlet pressure			Inlet total temperature		Suction rate, percent			Diffuser effectiveness, η , percent	Diffuser efficiency, ϵ , percent	Total pressure loss, $\Delta P/P$, percent	Exit rake position, L/H
		kg/sec	lbm/sec	Total	Static		K	°F	Inner wall	Outer wall	Total				
				N/cm ²	psia	N/cm ²									
1263	0.180	2.26	4.98	10.03	14.55	9.79	14.21	278	40	0	0	46.92	51.36	1.09	6
1264	.180	2.26	4.98	10.04	14.56	9.81	14.22			0	1.31	48.48	54.46	1.02	
1265	.181	2.25	4.97	10.03	14.55	9.79	14.21			0	2.0	52.61	56.69	.97	
1266	.180	2.26	4.98	10.02	14.53	9.78	14.19			1.34	2.76	59.60	63.03	.84	
1267	.182	2.27	5.01	10.01	14.51	9.77	14.17			2.36	3.45	64.16	66.21	.77	
1268	0.183	2.28	5.03	9.98	14.48	9.75	14.14	278	40	2.35	4.76	76.94	74.34	0.60	6
1269	.181	2.27	5.00	10.00	14.51	9.77	14.16			2.38	4.72	63.86	64.95	.80	
1270	.182	2.27	5.00	9.98	14.48	9.75	14.14			3.16	5.03	78.29	74.96	.58	
1271	.183	2.27	5.00	9.98	14.47	9.74	14.12			3.45	5.42	80.57	76.87	.54	
1272	.182	2.26	4.99	9.97	14.46	9.73	14.12			4.06	6.17	83.64	79.28	.47	
1273	0.183	2.28	5.02	9.96	14.45	9.73	14.12	278	40	4.50	6.35	84.34	80.66	0.45	6
1274	.183	2.27	5.01		14.44		14.11			4.51	7.06	88.85	83.35	.39	
1275	.183	2.27	5.01				14.11			4.51	7.08	88.53	83.29	.39	
1276	.184	2.28	5.03				14.11			4.96	7.44	87.54	81.67	.43	
1277	.183	2.27	5.00			9.27	14.10			8.42	7.25	88.40	84.80	.35	
1278	0.183	2.27	5.00	9.96	14.44	9.73	14.11	278	40	8.48	7.27	84.58	79.65	0.47	6
1279	.183	2.28	5.02	9.99	14.49	9.75	14.15			1.80	3.90	70.41	71.41	.66	
1280	.306	3.71	8.18	10.06	14.59	9.40	13.64			3.75	6.41	86.07	82.02	1.15	
1281	.309	3.74	8.24	10.06	14.59	9.40	13.63			3.73	6.34	85.95	82.35	1.15	
1282	.304	3.75	8.27	10.25	14.86	9.58	13.89			0	0	46.54	51.31	3.05	
1283	0.183	2.26	4.97	9.95	14.42	9.70	14.08	278	40	0	0	42.65	49.22	1.17	6
1284	.182	2.25	4.96	9.95	14.43	9.70	14.08					42.37	48.37	1.18	
1285	.301	3.69	8.14	10.18	14.77	9.52	13.81					43.06	48.76	3.16	
1286	.183	2.26	4.99	9.93	14.40	9.69	14.05					46.00	50.91	1.14	

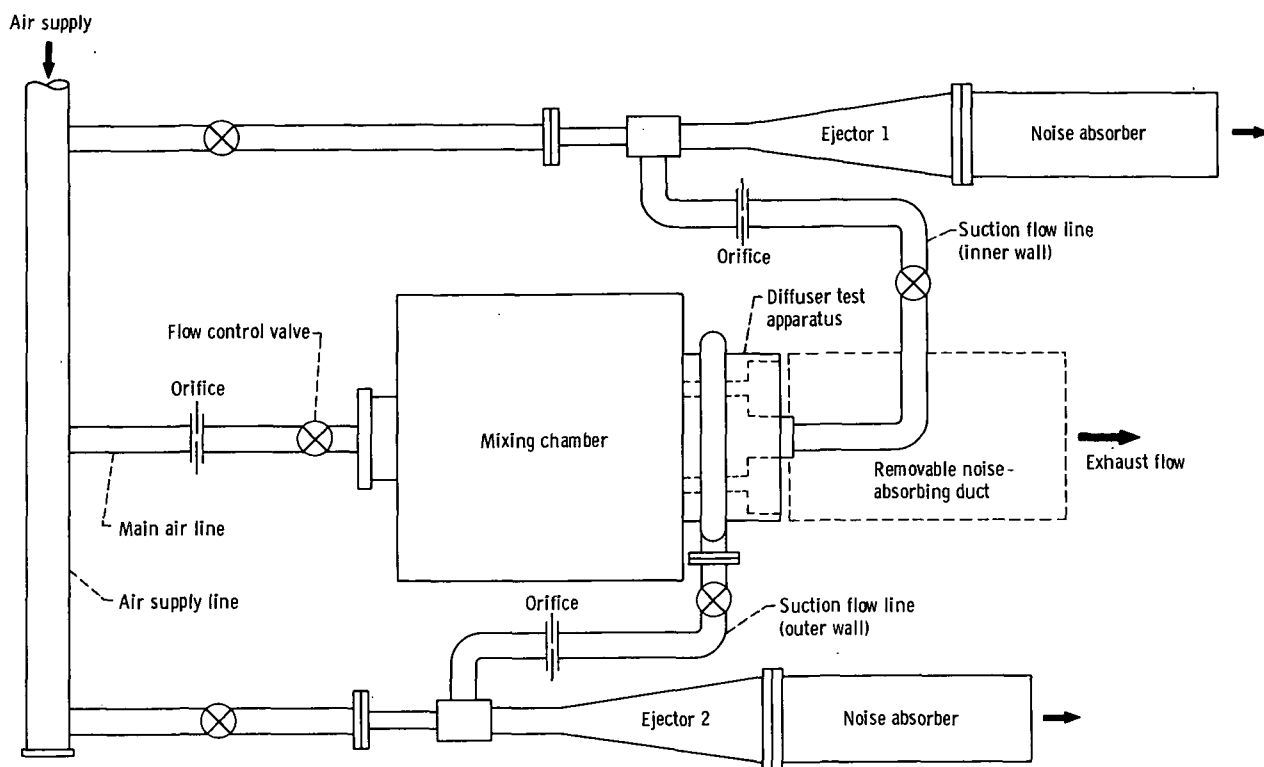


Figure 1. - Flow system.

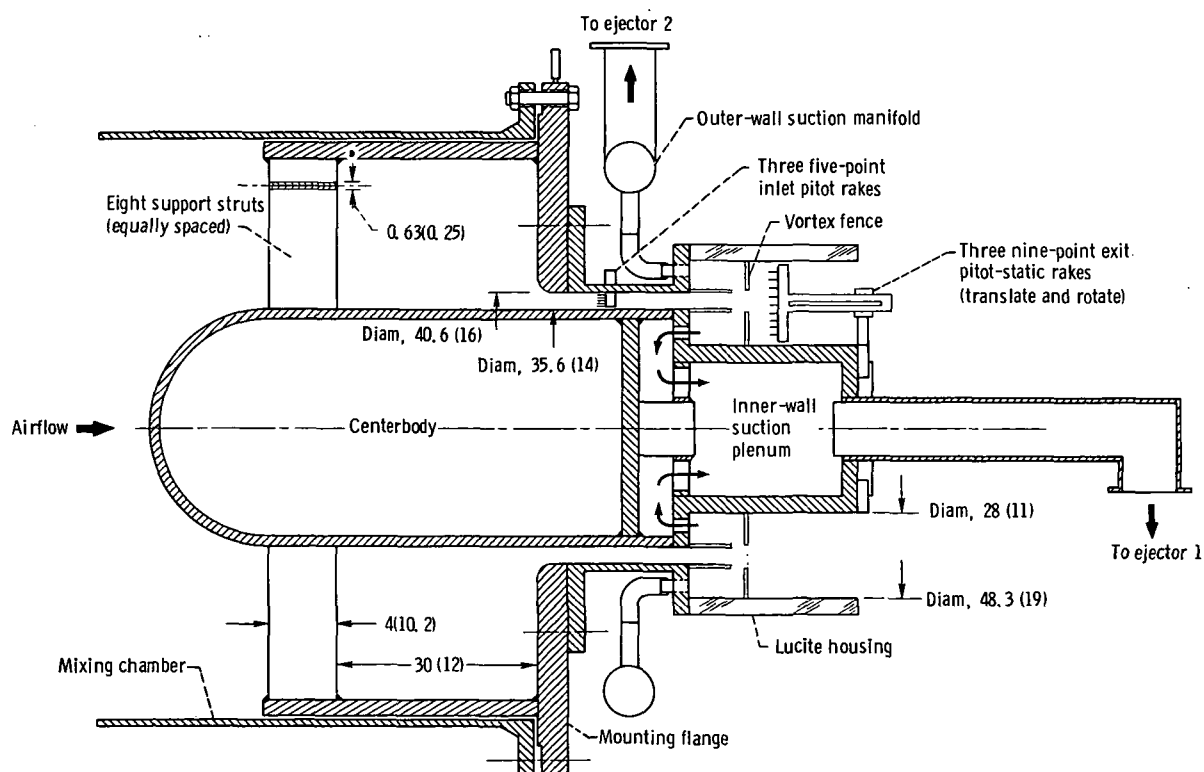
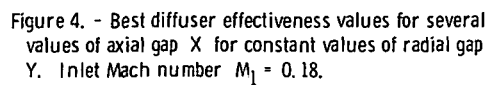
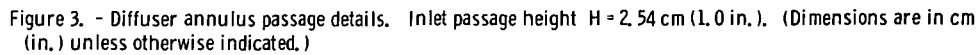
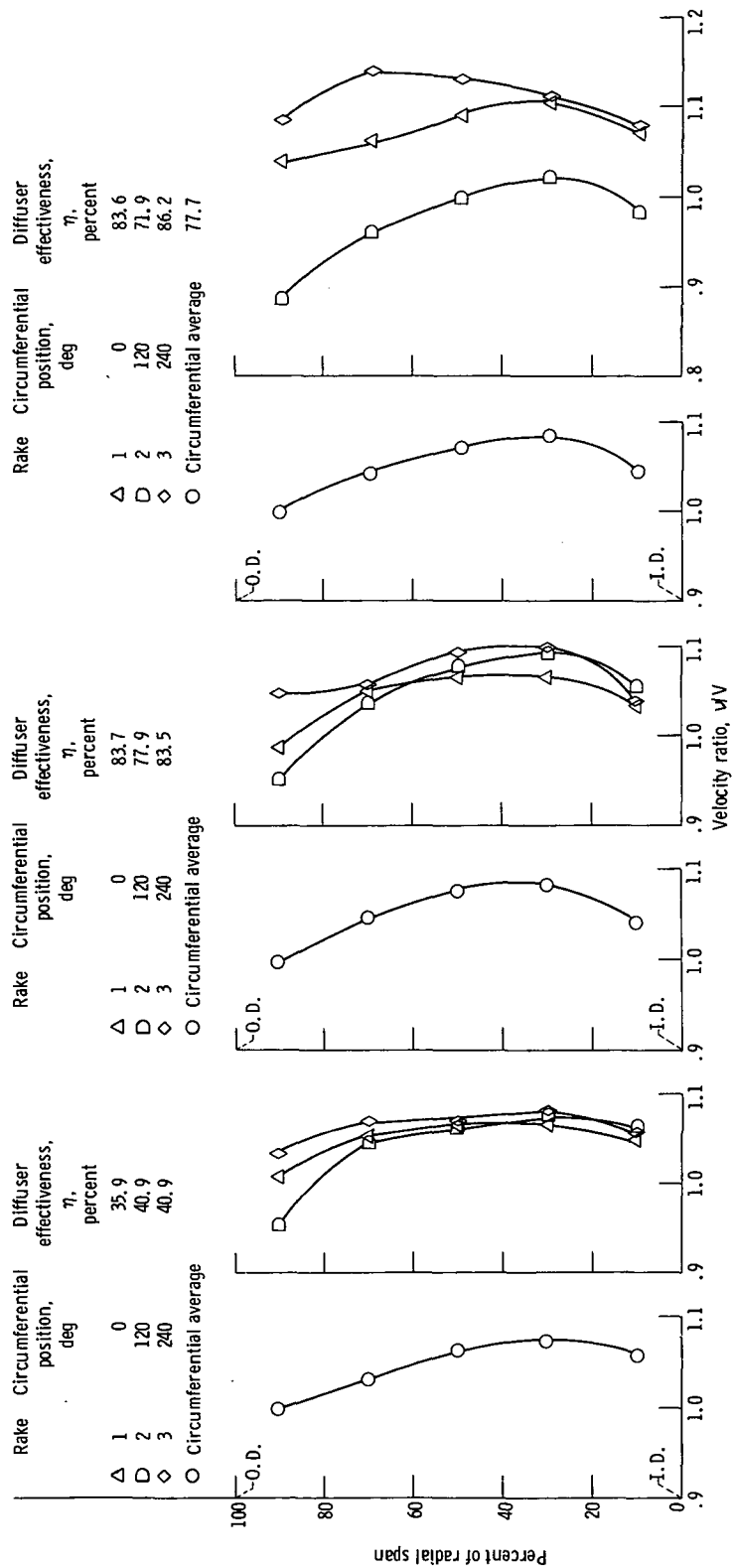
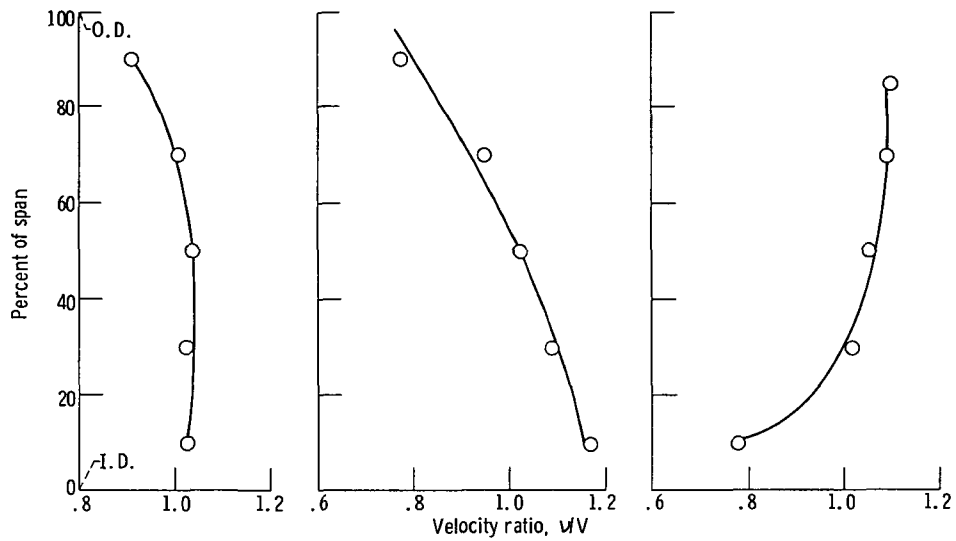


Figure 2. - Cross section of asymmetric annular diffuser test apparatus. (Dimensions are in cm (in.)).

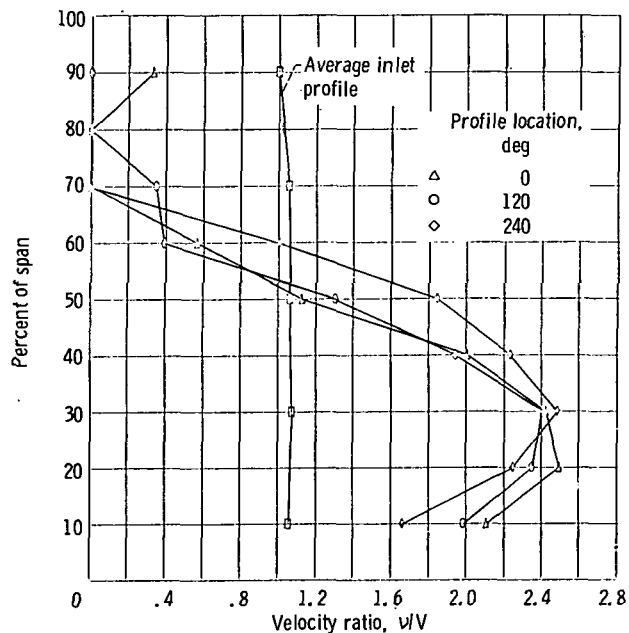




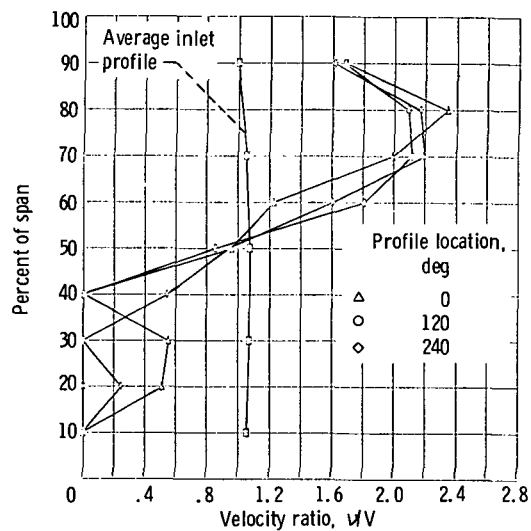


(a) No suction. (b) Inner wall suction rate $S_i = 4.1$; outer wall suction rate $S_o = 6.4$. (c) Inner wall suction rate $S_i = 3.1$; outer wall suction rate $S_o = 7.2$.

Figure 6. - Radial profiles of velocity at prediffuser exit station for various suction rate combinations.
Inlet Mach number $M_1 = 0.18$.

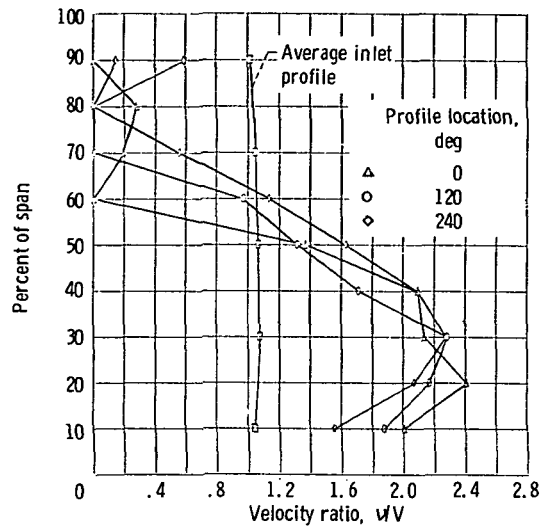


(a) Radial profiles of exit velocity at three circumferential locations showing hub bias by applying suction to inner wall vortex chamber and then removing suction prior to recording.

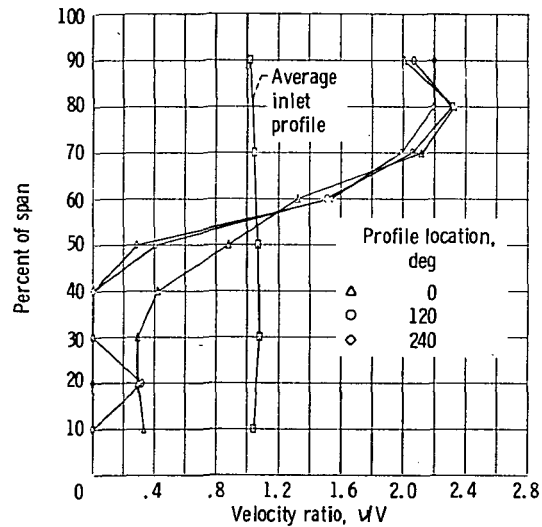


(b) Radial profiles of exit velocity at three circumferential locations showing tip bias by applying suction to outer wall vortex chamber and then removing suction prior to recording.

Figure 7. - Radial profiles of exit velocity without suction illustrating hysteresis. Inlet Mach number $M_1 = 0.18$.

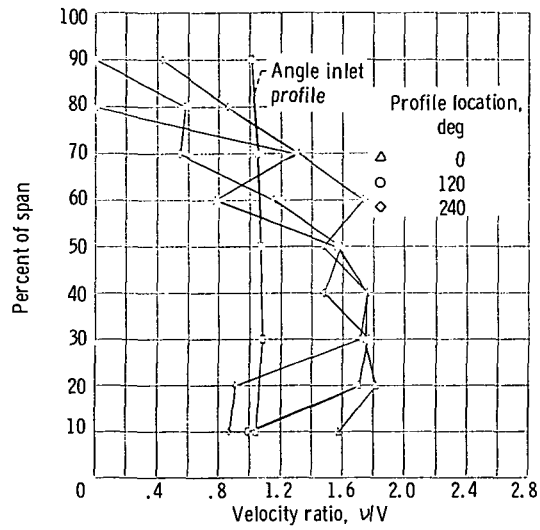


(a) Radial profiles of exit velocity at three circumferential locations showing hub bias by removing suction to outer wall vortex chamber momentarily and then reestablishing suction to outer wall prior to recording.

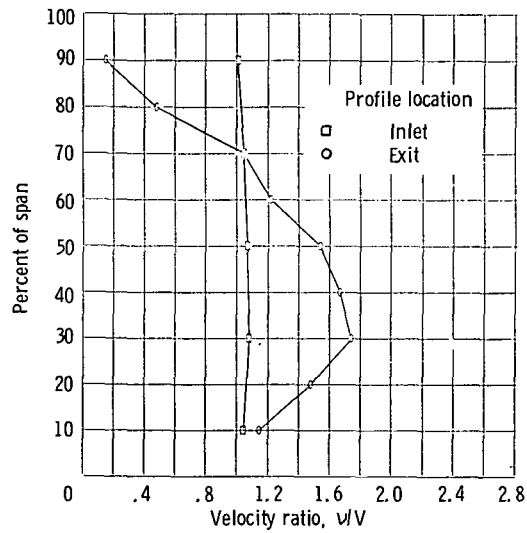


(b) Radial profiles of exit velocity at three circumferential locations showing tip bias by removing suction to inner wall vortex chamber momentarily and then reestablishing suction to inner wall prior to recording.

Figure 8. - Radial profiles of exit velocity at medium suction rates, illustrating hysteresis. Inlet Mach number, $M_1 = 0.18$; total suction rate $S_t = 6.2$ percent.



(a) Radial profiles at three circumferential locations.



(b) Circumferentially averaged radial profile.

Figure 9. - Radial profiles of exit velocity at high overall suction rate. Inlet Mach number $M_1 = 0.182$; total suction rate $S_t = 11.2$ percent.

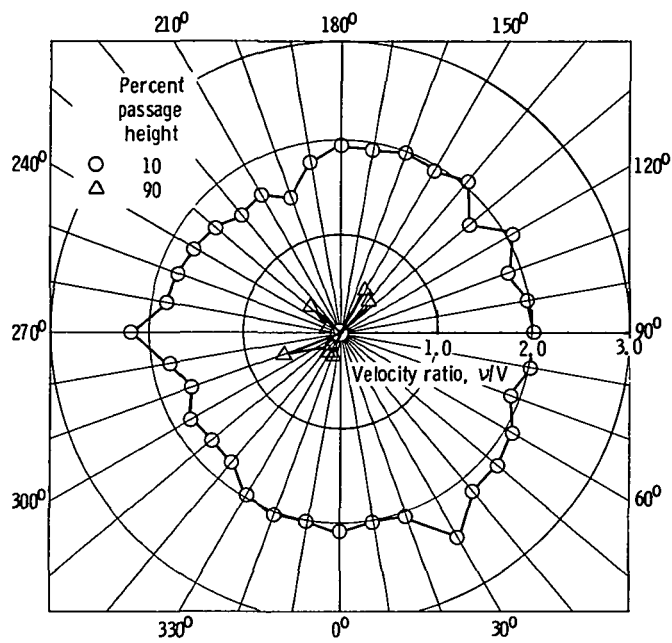
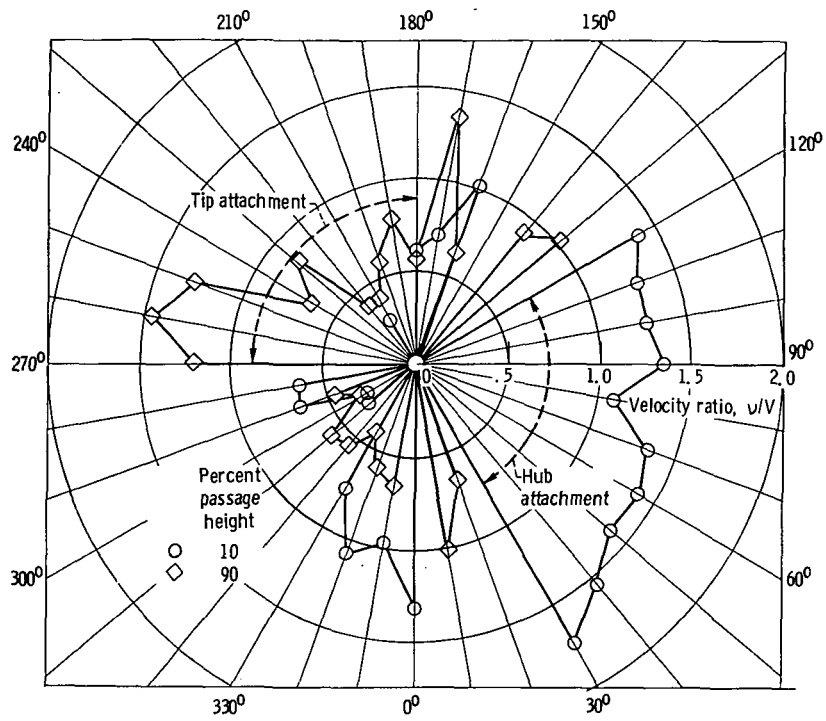
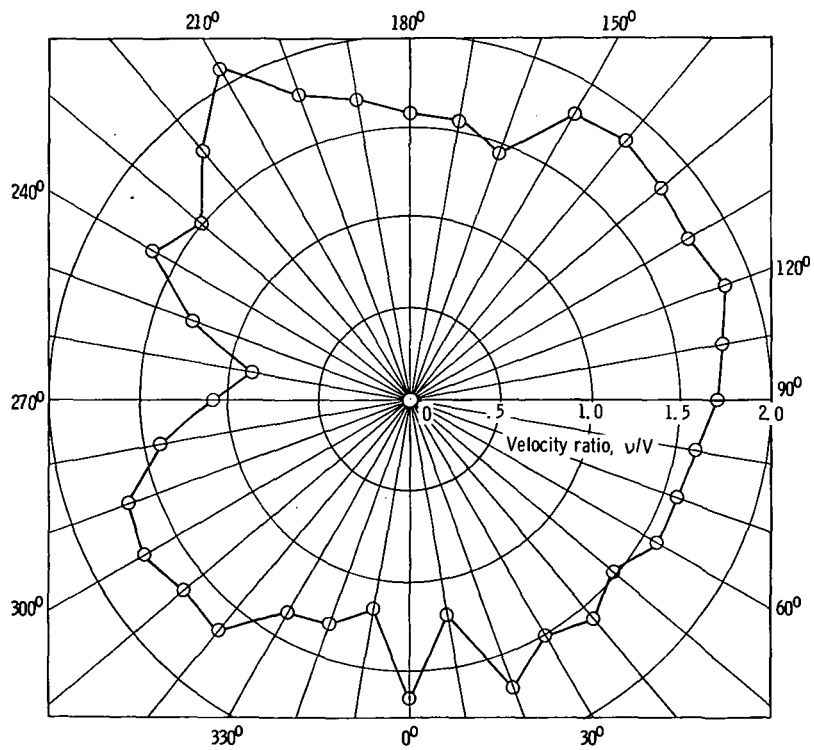


Figure 10. - Circumferential survey of exit velocity profiles at 10 and 90 percent of passage height at total suction rate of 6.2 percent. Inlet Mach number $M_1 = 0.18$; $X = 0.45$; $Y = 0.15$; exit rake position $U/H, 6.0$.

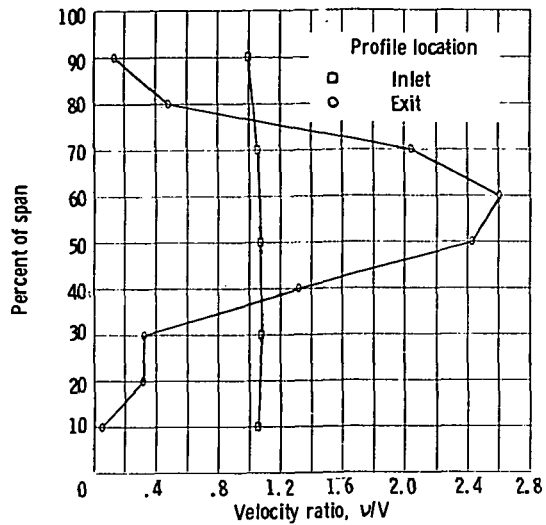


(a) Radial span position, 10 and 90 percent.

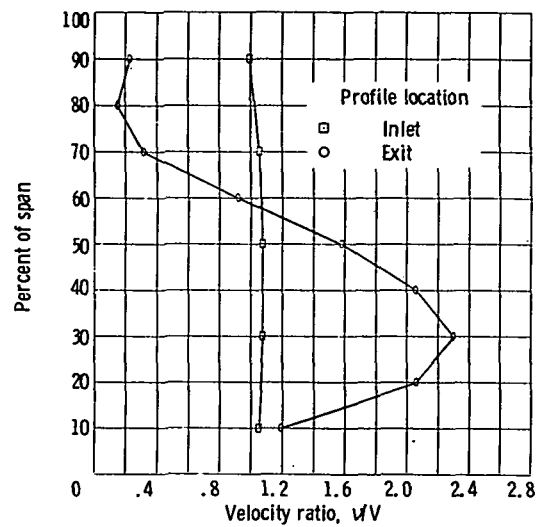


(b) Radial span position, 50 percent.

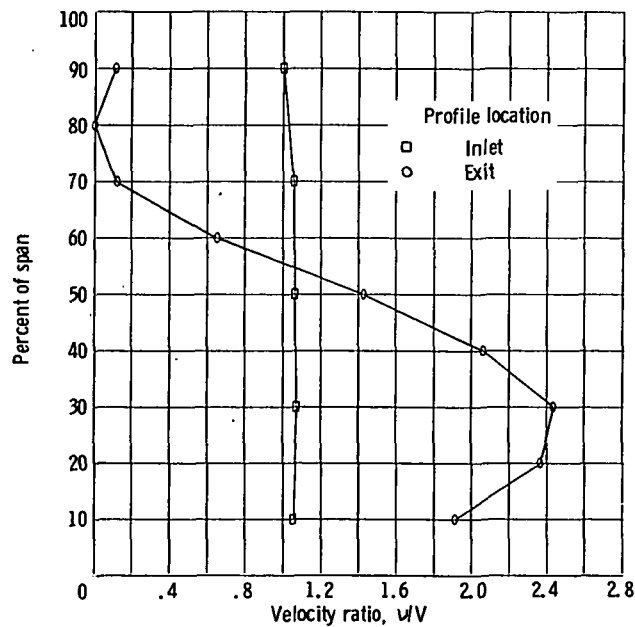
Figure 11. - Circumferential survey of velocity ratios at three radial span positions for a total suction rate of 10.2 percent. Inlet Mach number $M_1 = 0.18$, $X = 0.45$, $Y = 0.15$, exit rake position $L/H = 6.0$.



(a) Exit rake position $U/H = 2$; inlet Mach number $M_1 = 0.183$.

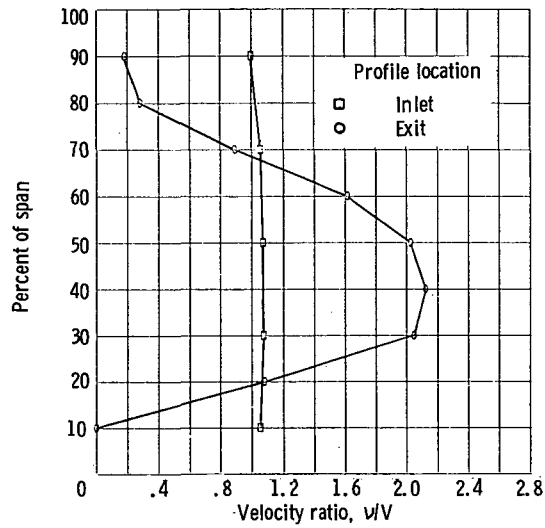


(b) Exit rake position $U/H = 4$; inlet Mach number $M_1 = 0.182$.

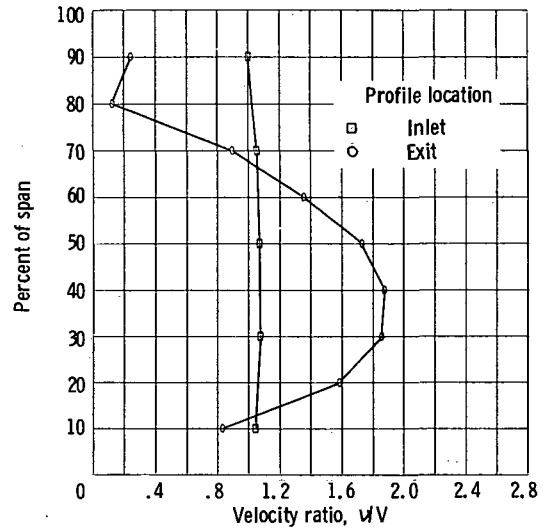


(c) Exit rake position $U/H = 6$; inlet Mach number $M_1 = 0.179$.

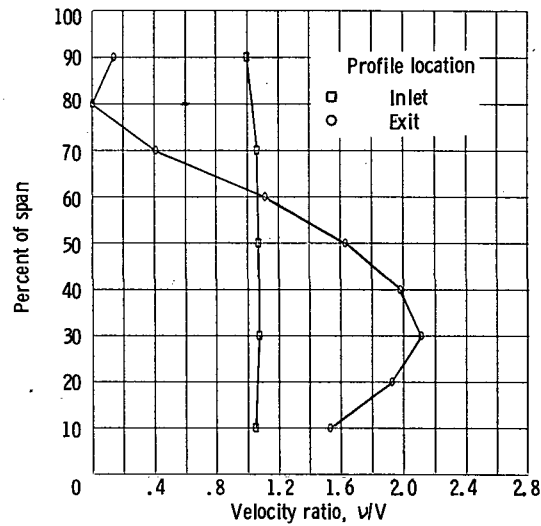
Figure 12. - Radial profiles of exit velocity at three different downstream positions for zero suction rate.



(a) Exit rake position $L/H = 2$; inlet Mach number $M_1 = 0.183$.



(b) Exit rake position $L/H = 4$; inner wall suction rate $S_i = 3.0$ percent; outer wall suction rate $S_o = 4.8$ percent; total suction rate $S_t = 7.8$ percent; inlet Mach number $M_1 = 0.183$.



(c) Exit rake position $L/H = 6$; inner wall suction rate $S_i = 3.2$ percent; outer wall suction rate $S_o = 5.1$ percent; total suction rate $S_t = 8.3$ percent; inlet Mach number $M_1 = 0.181$.

Figure 13. - Radial profiles of exit velocity at three different downstream positions. Nominal inner wall suction rate $S_i = 3$ percent; outer wall suction rate $S_o = 5$ percent.

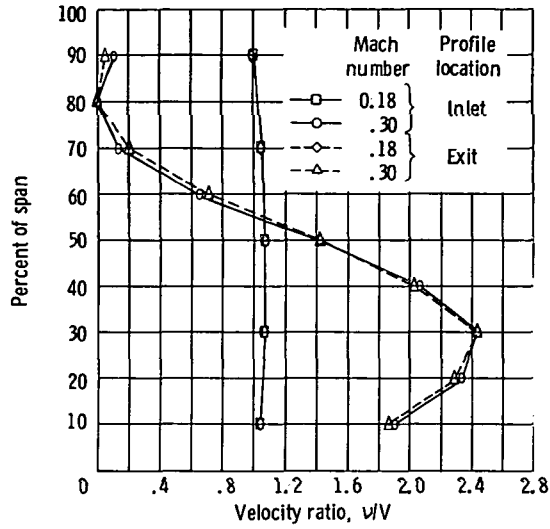


Figure 14. - Radial profiles of inlet and exit velocity for two inlet Mach numbers at zero suction rate.

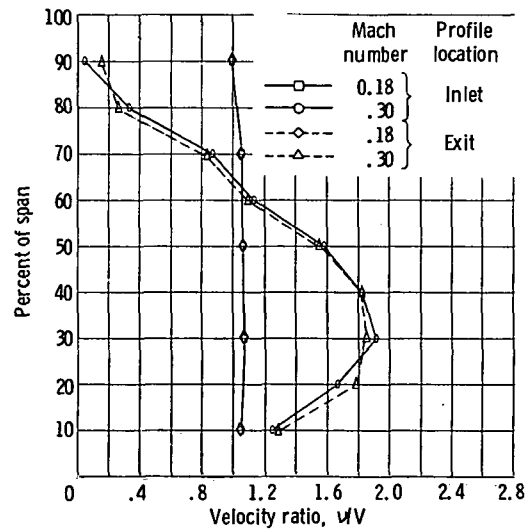


Figure 15. - Radial profiles of inlet and exit velocity for two inlet Mach numbers at a nominal suction rate of 3.6 percent on inner wall and 5.6 percent on outer wall.

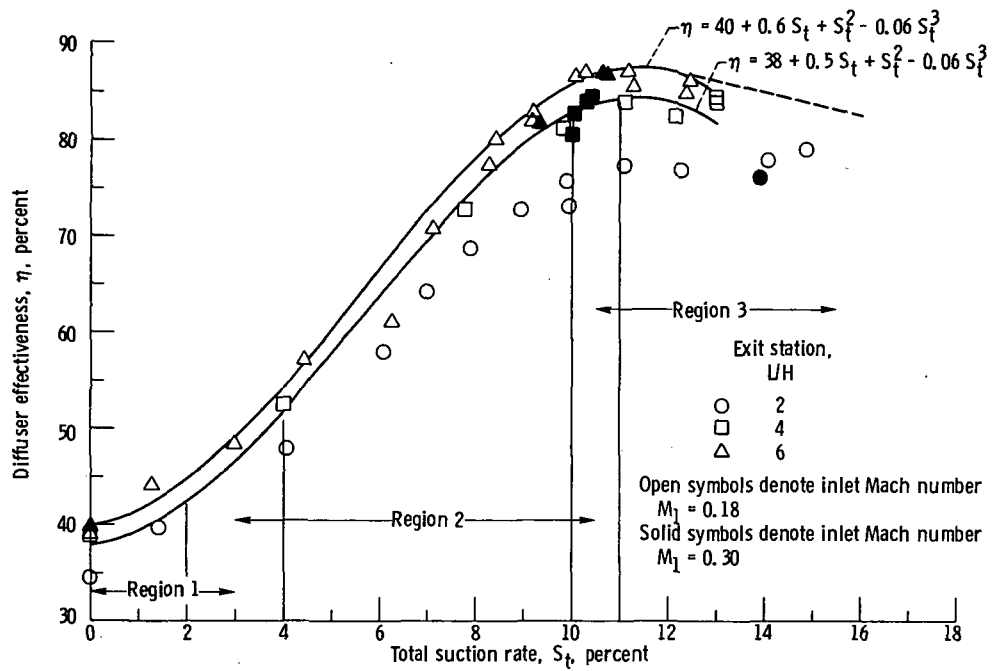


Figure 16. - Effect of suction on diffuser effectiveness for three exit stations and two inlet Mach numbers.

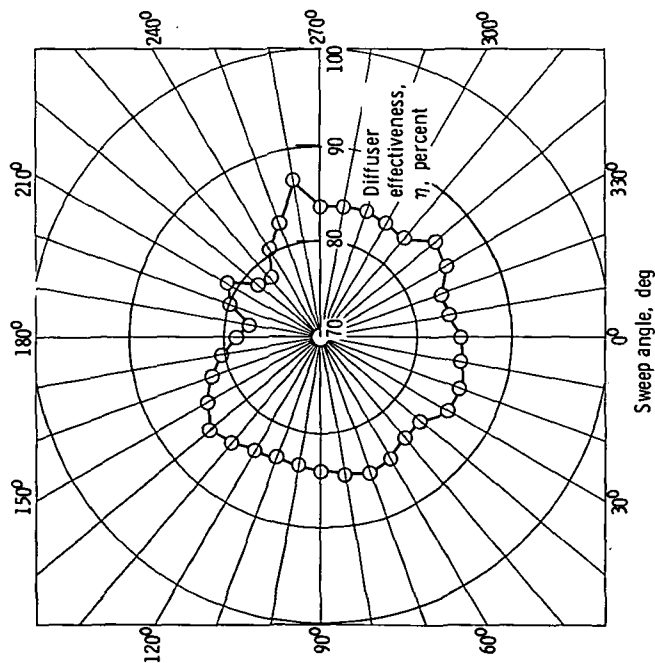


Figure 17. - Circumferential variation of diffuser effectiveness for total suction rate of 12.3 percent. Exit rake position $L/H = 6$, inlet Mach number $M_1 = 0.18$, $X = 0.45$, $Y = 0.15$.

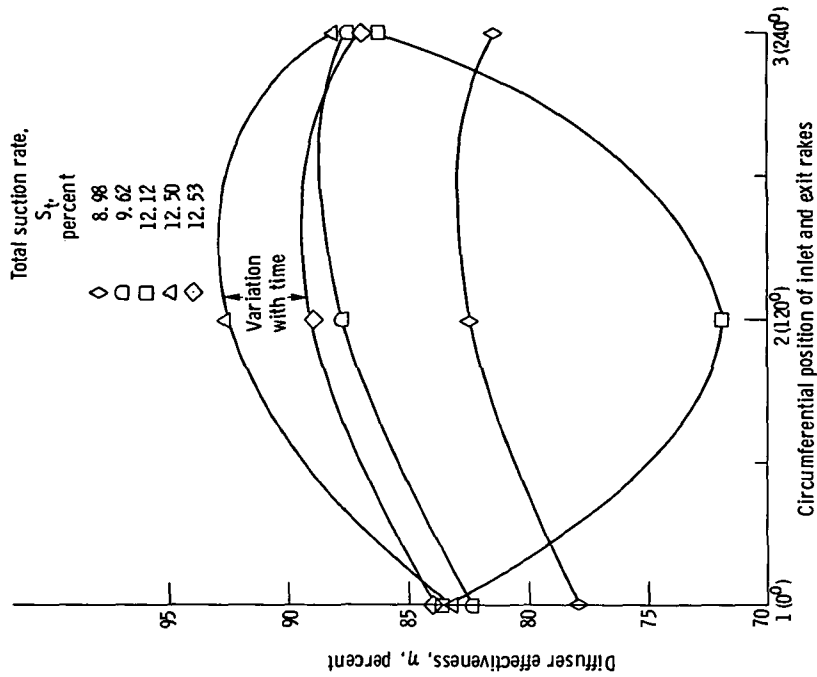


Figure 18. - Variation of diffuser effectiveness with circumferential position of pitot-static rakes for various suction rates. Exit rake position $L/H = 6$, $X = 0.40$, $Y = 0.15$.

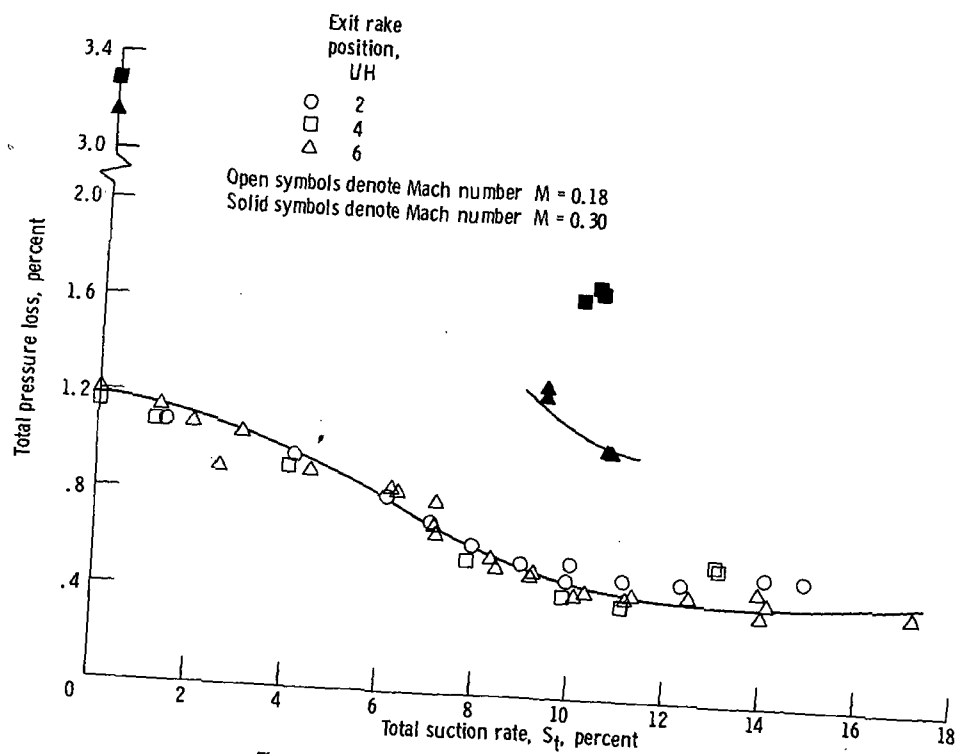


Figure 19. - Effect of suction on diffuser total pressure loss.



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